

Comparative analysis of spectra of the background of the proportional counter filled with Kr, enriched in ^{78}Kr , and with Kr of natural content

Yu. M. Gavriljuk,¹ V. N. Gavrin,¹ A. M. Gangapshev,¹ V. V. Kazalov,¹
V. V. Kuzminov,¹ S. I. Panasenکو,² and S. S. Ratkevich²

¹*Baksan Neutrino Observatory INR RAS, KBR, Russia*

²*Karazin Kharkiv National University, Ukraine*

(Dated: February 2, 2008)

The results of the experiment searching for 2K-capture with large low-background proportional counter are presented. The comparison of spectra of the background of the proportional counter filled with Kr enriched in ^{78}Kr (8400 hr) and with natural Kr (3039 hr) is given. A new limit on the half-life of ^{78}Kr with regard to 2K-capture, $T_{1/2} \geq 2.0 \cdot 10^{21}$ yrs (95% C.L.) has been obtained.

PACS numbers: 29.30.Kv

I. INTRODUCTION

The up to date experimental limit on the half-life of ^{78}Kr with regard to $2K(2\nu)$ -capture is $T_{1/2} \geq 1.5 \cdot 10^{21}$ yrs (90% C.L.) [1,2]. Theoretical calculations for this process based on different models predict the following half-lives for ^{78}Kr : $3.7 \cdot 10^{21}$ yrs [3]; $4.7 \cdot 10^{22}$ yrs [4]; $7.9 \cdot 10^{23}$ yrs [5]. The two values, from [4] and [5], have been obtained by estimating the half-life of ^{78}Kr with regard to the total number of $2e(2\nu)$ -captures, taking into account the portion of $2K(2\nu)$ -capture which constitutes 78.6%.

Comparison of experimental and theoretical results shows that sensitivity of measurement has reached the lower limit of theoretical predictions. This work presents a direct continuation of work [1] and differs from it in collected time of statistics which has increased from 159 hr to 8400 hr for measurements with enriched krypton.

II. THE TECHNIQUE OF THE EXPERIMENT

The reaction $^{78}\text{Kr}(2e_k, 2\nu)^{78}\text{Se}$ yields an atom of $^{78}\text{Se}^{**}$ with two vacancies on K-shell. The technique of the search for this reaction is based on the assumption that the energies of the characteristic photons and probabilities of their emission for filling the double vacancy coincide with the corresponding values for filling single vacancies of K-shell in two atoms of Se^* with single ionization each. In such a case the total registered energy is $2K_{ab}=25,3\text{keV}$, where K_{ab} is the binding energy of K-shell's electron in the atom of $\text{Se}(12.65\text{ keV})$. Fluorescence yield, due to the filling of the single vacancy on K-shell of Se, is 0.596. The energies and relative intensities of the characteristic lines of K-series are $K_{\alpha 1} = 11.22\text{ keV}$ (100%), $K_{\alpha 2} = 11.18\text{ keV}$ (52%), $K_{\beta 1} = 12.49\text{ keV}$ (21%), $K_{\beta 2} = 12.65\text{ keV}$ (1%) [6]. Probabilities of de-excitation with emission of Auger electron (e_a, e_a) only, or a single characteristic quantum and an Auger electron (K, e_a), or two characteristic quanta and low energy Auger electrons (K, K, e_a) are $p_1 = 0.163$, $p_2 = 0.482$ and $p_3 = 0.355$, respectively. In a gas, a characteristic quan-

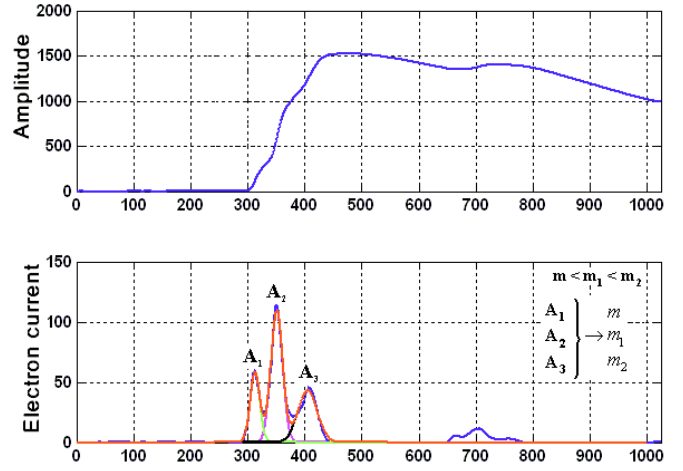


FIG. 1: Example of the real three-point pulse.

tum can pass a large enough distance from its place of origin to the place of its interaction. For instance, in krypton at a pressure of 4.35 atm ($\rho = 0.0164\text{ g/cm}^3$) 10% of the characteristic quanta with energies of 11.2 keV and 12.5 keV are absorbed at a distance of 1.83 and 2.42 mm, respectively (data on absorption coefficients were taken from work [7]). Runs of photoelectrons with the same energies are equal to 0.37 mm and 0.44 mm, respectively. They produce almost point-like energy release. In case of an event with emission of two characteristic quanta and their subsequent absorption in the working gas, the energy would be distributed in three point-like regions. It is these events with a unique set of characteristics that are the subject of the search presented in this paper (fig.1)

To register the 2K-capture process the large proportional counter (PC) with a body of copper of M1 type is used. The cylindrical body has the following inner dimensions: diameter of 140 mm, length of 710 mm. The anode wire made of gold-plated tungsten is stretched inside the cylinder along its axis, its diameter is 10 μm . The total volume of the counter is 10.4 l, the fiducial one is 9.16 l. PC is surrounded with low-background shield of 8 cm boron polyethylene (BP) + 15 cm Pb + 18 cm

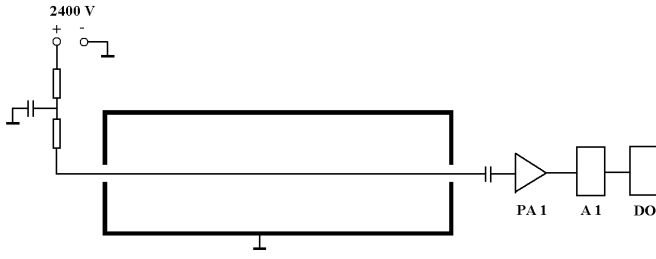


FIG. 2: The electric scheme of installation. PA1 - preamplifiers, A1 - amplifiers, DO - digital oscilloscope.

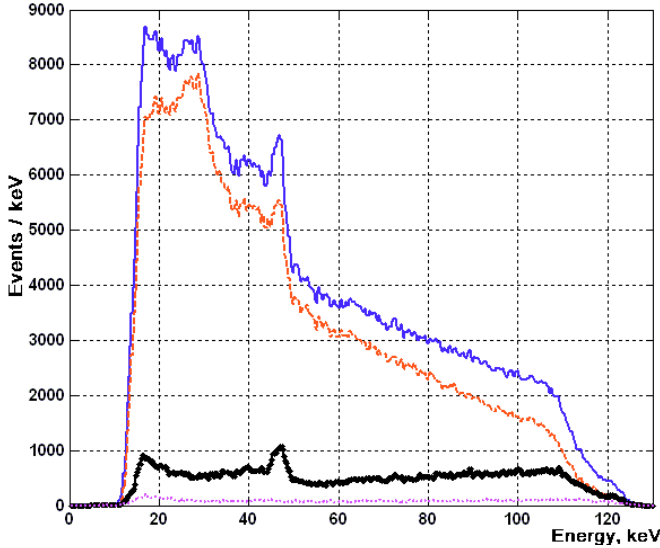


FIG. 3: Spectrum of PC's background for krypton enriched in ^{78}Kr (8400 hr): solid curve - all the events; dashed curve - single point-like events; dot-and-dash line - two point-like events; dotted line - three point-like events.

Cu. Pressure of krypton in the PC is 4.51 atm. In basic measurements we use the sample of krypton with volume of 47.65 l enriched in ^{78}Kr up to 99.81% at the FSUE PA "Electrochemical plant" of Zelenogorsk city. The set-up is located in the separate room of the underground laboratories of the Galium Germanium Neutrino Telescope of the Baksan Underground Neutrino Observatory, INR RAS, at a depth of 4700 m. w. e.

The total electrical design of the apparatus is presented in fig.2. High voltage (2400 V) is applied to the anode. A signal passes via the high-voltage coupling capacitor to the charge-sensitive preamplifier (PA). After amplification in the additional amplifier (A) the pulses go to the input of the digital oscilloscope (DA) LA-n20-12PCI incorporated into a personal computer which writes down their shape digitized with 6.25 MHz frequency.

The registered pulses are then processed to determine the shape of current pulses of the primary ionization electrons. Electron current for a point-like event has the Gaussian shape. This fact is used to determine the amount of the similar-to-point-like components in each event by modeling it with a set of Gauss functions (fig.1).

The amplitude of each component (A) is determined by the area under the Gaussian. Analysis of each component's amplitude is performed for each event. The basic parameter of the analysis is the ratio of amplitudes of the components in a current pulse (fig.1). For this purpose the amplitudes are sized in increasing order independently of their arrival time (m_i). In addition to the main pulse there is a secondary pulse in fig.1 which is due to photoelectrons knocked out from the copper body of PC by photons generated in the electron avalanches in the process of gas amplification. The delay between the pulse and the after-pulse is determined by the total drift time of electrons from the cathode to the anode. It defines the time interval within which any single event could be kept independently of the distribution of primary ionization over the PC volume.

In fig.3 are given spectra of PC's background collected during 8400 hr with krypton enriched in ^{78}Kr : solid curve for all events, dashed curve for single point-like events, dot-and-dash line for two point-like events and dotted line for three point-like events. One can see the peak of total absorption of γ -line for ^{210}Pb at energy of 46.5 keV in the total spectrum (solid curve). Such a peak should be mainly composed of single point-like events (photoeffect in krypton with the de-excitation by Auger-electrons) and by two point-like events (photoeffect with characteristic emission of krypton). Small part of events with absorption of the primary (or characteristic) photon through its scattering on the outer electrons with the subsequent followed by the absorption of the secondary quantum would be three point-like. Broad peaks, at lower energies, are due to conversion electrons of the same line (ce- L_1 : =30.1 keV, 52%; ce-: =43,3 keV, 13,6% [8]), coming from the surface copper layer. All the events in these peaks should be single point-like. Conversion electrons are accompanied with L-series characteristic quanta's and low energy Auger-electrons (M-series characteristic quanta) or with Auger-electrons from L-shell of ^{210}Bi . Double point-like event occur if the characteristic photon absorbed in a working gas simultaneously with conversion electron coming from the counter wall. A part of such events is small. This quantitative picture is supported by the distribution of events taken from different peaks of the spectra of corresponding types. Comparison of the obtained ratio of areas of the peak of 46.5 keV for different components with theoretical calculations allows one to determine the efficiency of the computer event selection carried out for specified regions of ionization.

In fig.4 one can see the total spectrum of three point-like events (the upper curve) and a spectrum of events selected from the first one after application of the following conditions on the components $2.0 \text{ keV} \geq m \geq 6.0 \text{ keV}$ and $m_1/m_2 \leq 0.6$ which include a set of characteristics corresponding to the searched-for events (the lower curve). In the second spectrum, one can see a peak at 25-30 keV which is similar to the expected one for the 2K-capture.

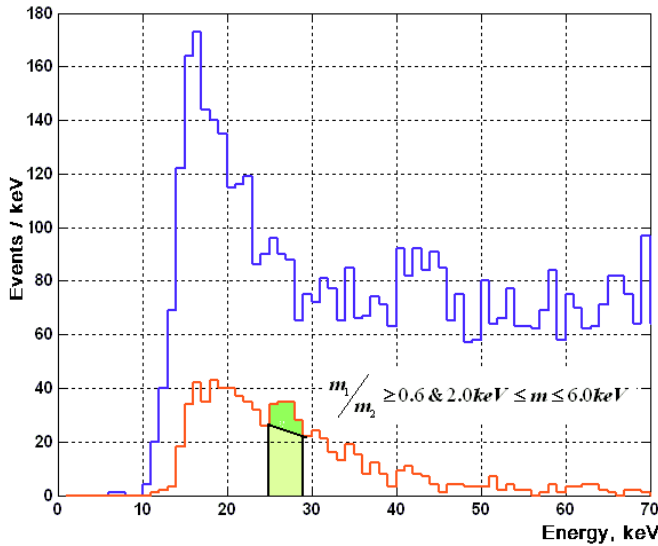


FIG. 4: Spectrum of three point-like ^{78}Kr events before and after the selection.

To clarify the nature of this peak an additional measurement was carried out concerning the background of PC filled with natural krypton (0.354% ^{78}Kr [9]). A radioactive isotope ^{85}Kr with volume activity of 1000 Bq/l Kr is present in natural krypton. It comes into the atmosphere mainly through the processing of the debuggings of the fuel of atomic stations. To eliminate this component from the PC's background the sample of natural krypton was undergone an isotopic purification by the way of centrifugation at the Electrochemical Plant in Zelongorsk city.

In fig.5 are given spectra of the PC background collected during 3039 hours with natural krypton at a pressure of 4.51 at: solid curve for all events, dashed curve for single point-like events, dot-and-dash line for two point-like events and dotted line for three point-like events. Atmospheric krypton contains also cosmogenic radioactive isotope ^{81}Kr ($t_{1/2} = 2.1 \times 10^5$ yrs [9]) with volume activity of $0.1 \text{ min}^{-1} \text{ l}^{-1}$ Kr [10,11]. It decays by capturing an electron and gives ^{81}Br (K-capture - 87.5% [12]). In case of K-capture the release of energy is equal to 13.5 keV. One can easily see this peak in fig.5.

Two spectra are presented for comparison in fig.6 for three point-like events for krypton enriched in ^{78}Kr (dashed curve), and for krypton of natural content (solid curve), scaled down to the same time. As is seen, they are in good agreement. Slight difference seen at energies higher than 90 keV could possibly be explained by the presence of the residual ^{85}Kr in the sample of natural krypton. At high enough energies the distribution of ionization along the track of an electron in its projection onto the PC's radius could simulate multiple-point events. Fig.7 shows the two spectra for three point-like events selected under the mentioned conditions for both samples. One can see that there is a peak at 25-30 keV in natural krypton spectrum with the intensity analogous

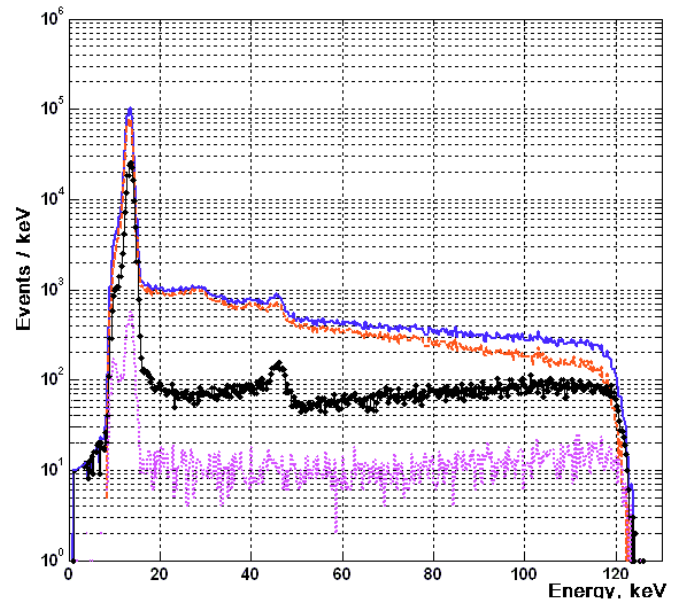


FIG. 5: Spectrum of the background of PC filled with krypton of natural content during 3039 hours: solid curve for all events; dashed curve for single point-like events; dot-and-dash line for two point-like events; dotted line for three point-like events.

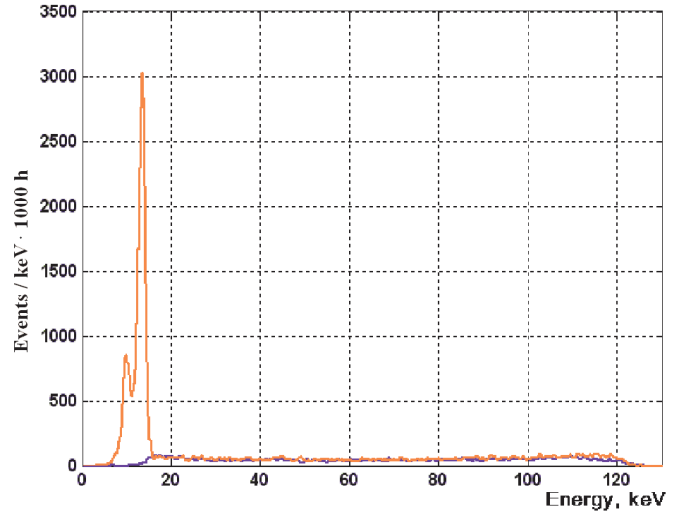


FIG. 6: Three point-like events for natural krypton (solid curve) and for krypton enriched in ^{78}Kr (dashed curve).

to that of the peak in the spectrum for krypton enriched in ^{78}Kr . Presently we carry out thorough investigation into the origin of this background peak. However, it is possible to estimate the limit on the 2K-capture contribution into the spectrum under study. In case we assign all the observed effect to 2K-capture, the effect does not exceed the area of the peak multiplied by a factor of two standard deviations at a confidence level of 95%.

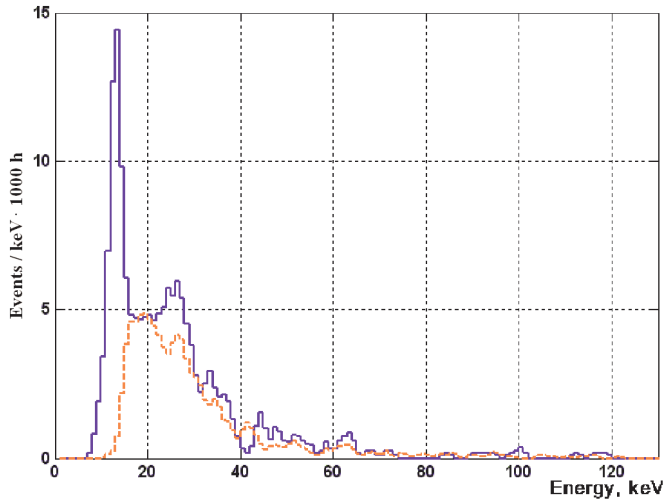


FIG. 7: Spectra for three point-like events selected under mentioned conditions for natural krypton (solid curve) and krypton enriched in ^{78}Kr (dashed curve).

Half-life limit was determined by:

$$T_{1/2} = \frac{\ln 2 \times N \times \varepsilon_1 \times \varepsilon_2 \times p_3 \times (p_4 + p_5)}{N_{\text{eff}}}$$

where $\ln 2 = 0.693$; $N = 1.08 \cdot 10^{24}$ ^{78}Kr atoms; $\varepsilon_1 = 0.809$ is the efficiency of three point-like events registration; $\varepsilon_2 = 0.43$ is the efficiency of the three point-like events selection; $p_3 = 0.355$; $p_4 = 0.713$; $p_5 = 0.213$; $N_{\text{eff}} \leq 46 \text{ yr}^{-1}$, and was found to be

$$T_{1/2}(2K, 2\nu) \geq 2 \cdot 10^{21} \text{ yr (95\% C.L.)}.$$

The work has been carried out under the financial support of the RFBR (grant no. 04-02-16037) and "Neutrino Physics" Program of the Presidium of RAS.

-
- [1] Ju.M. Gavriljuk et al. Phys. of Atomic Nuclei, 2006, Vol.69, No.12, pp.2124-2128.
 - [2] V.V. Kazalov, Results of analysis of experimental data of search for $2K(2\nu)$ -capture of ^{78}Kr , report presented at the Baksan Youth School of Experimental and Theoretical Physics - 2005, 17-22 April 2006, Elbrus village, Kabardino-Balkaria, Russia. 2006, M., 2007, p.73-78.(in Russian.)
 - [3] M. Aunola, J. Suchonen, Nucl. Phys., A602, (1996), p. 133.
 - [4] M. Hirsh et al. Nucl. Phys., A347, (1994), p. 151.
 - [5] O.A. Rumyantsev and M. Urin, Phys. Lett., B443, (1998), p. 51.
 - [6] M.A. Blokink, I.P. Schweizer. *Rentgenospectralny spravochnik*. (M.: Nauka, 1982)(in Russian).
 - [7] *Sechenie vzaimodeistvia gamma izluchenia*. E. Storm, Kh. Israel. (Spravochnik M.: Atomizdat, 1973) (in Russian).
 - [8] *Scheme decay of radionuclide. Energy and intensity of radiation*. Doklad 38 MKRE. (M.: Energoatomizdat, 1987) (in Russian).
 - [9] *Table physical magnitude*. Spravochnik, editor: I.K. Kikoin. (M.: Atomizdat, 1976) (in Russian).
 - [10] H.H. Loosli and H. Oeschger, Earth Plan. Sci. Lett., 7, 1, (1968), p. 67.
 - [11] V.V. Kuzminov and A.A. Pomansky, Radiocarbon, 22, 2, (1980), p. 311
 - [12] W.M.Chew et al., Nucl. Phys., A229, 1, (1974), p. 79.